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TWO-PHASE CRITICAL DISCHARGE OF HIGH PRESSURE LIQUID NITROGEN

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TWO-PHASE CRITICAL DISCHARGE OF HIGH PRESSURE LIQUID NITROGEN

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SUMMARY

Experimental data are reported for the two-phase critical flow of saturated and subcooled liquid nitrogen through a convergent-divergent nozzle. The nozzle inlet conditions range from highly subcooled liquid ($P_o = 42$ atm, $T_o = 90$ °K) to conditions very near the thermodynamic critical point. The results show that liquid nitrogen exhibits the same general nozzle behavior as water and is in agreement with a recent two-phase critical flow model.

INTRODUCTION

The two-phase critical discharge of saturated and subcooled liquids is of interest in the space, nuclear reactor, and desalinization industries. Experiments resulting from such interest have produced a wealth of data for water and liquid alkali metals. However, little data has been accumulated for liquid cryogens discharging through converging nozzles. Some comparatively low temperature data available are the carbon-dioxide results reported in reference 1.

The purpose of this study is to measure the critical discharge rates for saturated and subcooled liquid nitrogen in a converging-diverging nozzle for inlet conditions ranging from highly subcooled

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liquid ($P_o = 42$ atm, $T_o = 90^o$ K) to those very near the thermodynamic critical point. The stagnation pressure and temperature reduced against the thermodynamic critical point ranged from 0.33 to 1.25 and 0.70 to 1.00 respectively. The data will be compared to a recent model[2] to discern if the model is general enough to describe cryogenic conditions.

MODEL

As shown by Henry and Fauske[2], the critical flow rate of a liquid-vapor mixture can be expressed by:

$$G_c^2 = - \left\{ k \left[[1 + x(k - 1)] \, x \frac{dv_g}{dP} + \left[v_g [1 + 2x(k - 1)] + kv_l [2(x - 1) + k(1 - 2x)] \right] \frac{dx}{dP} + k[1 + x(k - 2) - x^2(k - 1)] \frac{dv_l}{dP} + x(1 - x) \left(kv_l - \frac{v_g}{k} \right) \frac{dk}{dP} \right]^{-1} \right\}_t \quad (1)$$

For saturated or subcooled liquids in converging nozzles the following assumptions are made[2].

1. The amount of vapor formed during the expansion from the inlet to the throat is negligible ($x_t \approx 0$). Therefore, the momentum equation relating these two locations is simply a single phase Bernoulli expression.

$$\eta = 1 - \left(v_{lo} G_c^2 / 2P_o \right) \quad (2)$$

2. The liquid phase is incompressible.

$$dv_l / dP = 0 \quad (3)$$

3. The vapor that is formed at the throat is in equilibrium at the local pressure.
4. For $P_o/P_c > .05$ the liquid and vapor velocities are equal ($k \approx 1$).
5. The rate of mass transfer at the throat can be formulated as proposed by Henry et. al.[3] i.e.

$$\left(\frac{dx}{dP}\right)_t = \left[\frac{N}{(S_{gE} - S_{lE})}\frac{ds_{lE}}{dP}\right]_t \tag{4}$$

where $N = x_E/0.14$. The value for N was determined from the steam-water data of Starkman et. al.[4].

Under these assumptions, the critical flow rate expression can be written as:

$$G_c^2 = \left[\frac{N(v_{gE} - v_{lo})}{(S_{gE} - S_{lE})}\frac{ds_{lE}}{dP}\right]_t^{-1} \tag{5}$$

Equations (2) and (5) were solved simultaneously for the critical flow rate and pressure ratio.

EXPERIMENTAL APPARATUS

The essential features of the test apparatus are shown in figure 1. The stagnation chamber was a large volume properly baffled to avoid jetting. The test nozzle was an axisymmetric venturi flow meter which was adapted for use in this experiment. The nozzle was instrumented with nine pressure taps as shown in figure 1. The stagnation temperature was measured with two platimum resistance thermometers. Flow-rates were metered with two venturi flow meters in series.

The test section assembly was placed in a cryogenic blowdown facility. The blowdown system could operate for about 12 minutes at the maximum flow rate of the present test. Liquid nitrogen could be delivered to the stagnation chamber at the desired pressure and temperature, from 90 - 127 $^{\circ}$K and up to 42 atm. Throughout the blowdown time the fluid would steadily rise in temperature. It could be held at a given temperature to a tolerance of about ± 0.1 $^{\circ}$K for about 30 seconds, which was sufficient for this test. The majority of the data were recorded electronically on a high speed data acquisition system.

In this experiment each data point represented two runs taken at different back pressures to demonstrate choking.

DISCUSSION OF RESULTS

Several axial pressure profiles were measured with $P_o/P_c \approx 1.01$ and $T_o/T_c \approx 1.00$ and are shown in figure 2. Figure 2 also shows profiles taken at $P_o/P_c = 1.05$ and $T_o/T_c = 0.94$, a subcooled condition. The profiles at the throat and upstream are unaffected by the downstream pressure distribution, indicating a choked flow. The data reproducibility from run to run is good.

The flow rates for the near-critical stagnation conditions are comparable to those for saturated nitrogen away from the critical point, (see also figure 3). Despite the fact that the stagnation conditions are very near the thermodynamic critical point, no anomoly, such as a sharp reduction in flow rate, was observed.

The critical flow rate and pressure ratio data are compared to the analytical model of reference 2 in figures 3a and 3b respectively. The agreement between the model and the flow rate data is good over the pressure and temperature ranges investigated. The agreement with the critical pressure ratio data is good at high subcoolings and close to saturation. There is a very definite break in the $T_0 = 110\ ^{\circ}K$ critical pressure ratio data at $P_0 \approx 30$ atm. At this point on the corresponding critical flow rate plot the data exhibit an inflexion point. It is believed that this behavior is a function of the particular contour of the nozzle employed in this study. The changes in the curve are felt to be indicative of a changing flow pattern just upstream of the throat. A combination of the rapid convergence, comparatively sharp corner, high velocity, and high density fluid can promote sizable two-dimensional effects and local cavitation. This promotes a preferential separation of the phases which has been demonstrated to have a significant effect on the system compressibility[5]. Such problems are not unusual for this type of nozzle flow[4,6]. At the larger subcoolings the liquid is sufficiently below saturation to remain in an all liquid state even if there is a sharp corner.

It should be emphasized that when the nozzle was tested in low velocity single phase liquid flows and choked gas flows it behaved, for all practical purposes, as an ideal nozzle. This illustrates how difficult it is to obtain definitive data in high velocity-high density flows in which phase change occurs.

The data show that liquid nitrogen behaves much the same way as the water data reported in reference 7. It also shows that the model

of reference 2 affords a good overall prediction of the phenomenom and can be used to perform design calculations for such systems.

It is important that the data discussed herein are not equated to the discharge of saturated and subcooled liquids through sharp edged orifices[8,9]. As discussed in reference 2, such flows have a unique flow pattern and can be closely approximated by the standard incompressible orifice equation.

NOMENCLATURE

G - flow rate per unit area

k - velocity ratio, u_g/u_l

N - experimental parameter

P - pressure

s - entropy

T - temperature

u - velocity

v - specific volume

x - quality

η - critical pressure ratio, P_t/P_o

SUBSCRIPTS

c - critical flow condition or thermodynamic critical point

E - equilibrium (corresponding to local static pressure)

g - vapor phase

l - liquid phase

o - stagnation

t - throat

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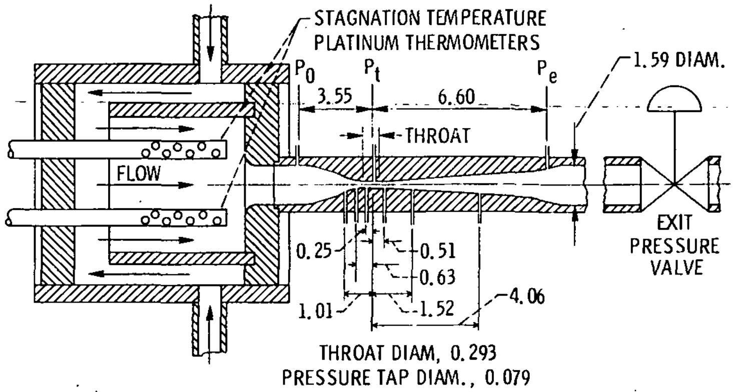

Figure 1. - Test section assembly. (All dimensions in cm.)

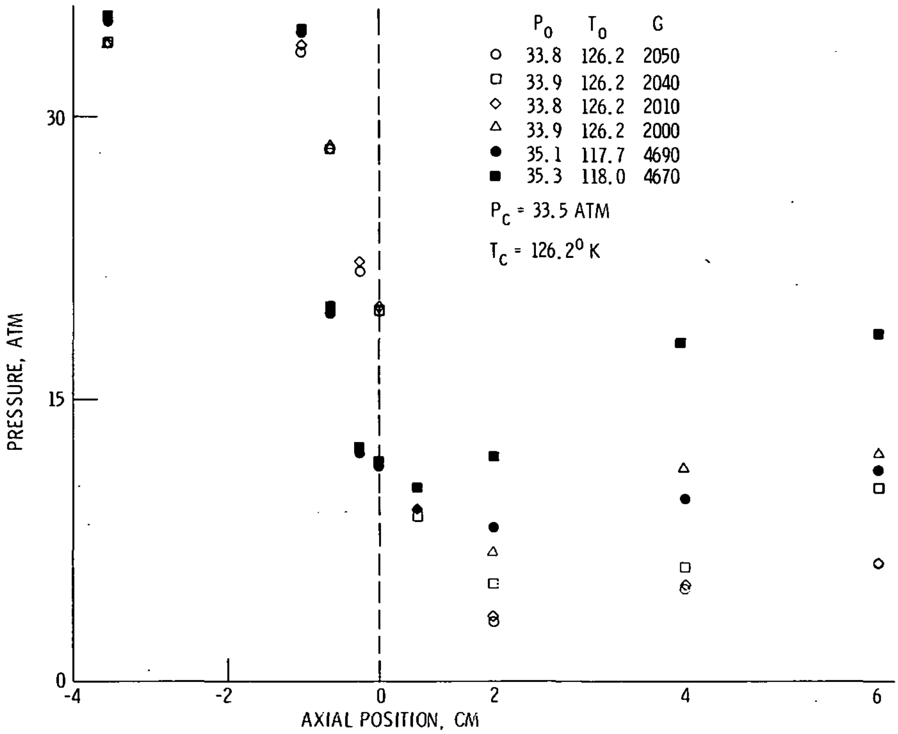

Figure 2. - Nozzle pressure profiles with near-critical stagnation conditions.

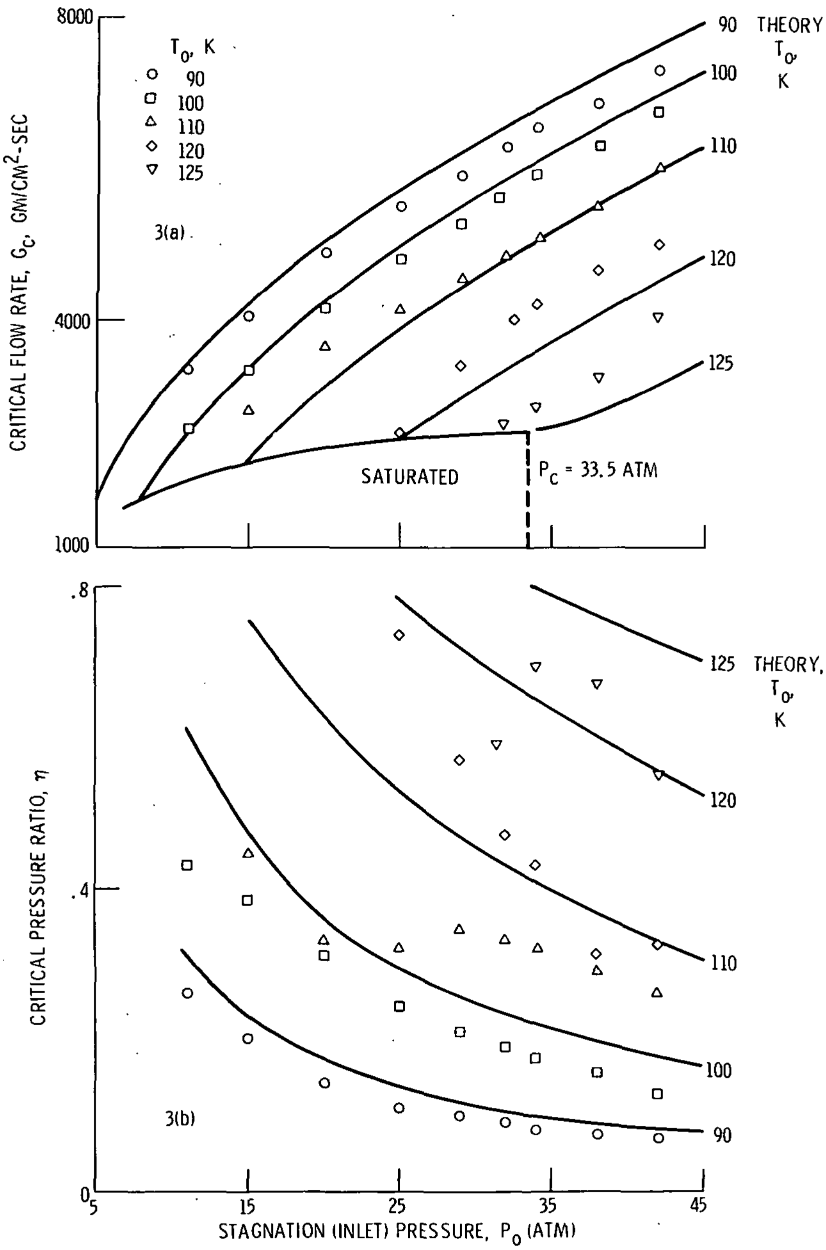

Figure 3. - Critical flowrate and pressure ratio.